Biological Conservation 203 (2016) 290–297

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/bioc

Contrasting spatial and temporal trends of protected area effectiveness in mitigating deforestation in Madagascar

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ARTICLE INFO

Article history:
Received 25 April 2016
Received in revised form 19 August 2016
Accepted 30 September 2016
Available online xxxx

Keywords:
Protected areas
Deforestation
Effectiveness
Impact evaluation
Conservation
Madagascar

ABSTRACT

Networks of protected areas (PAs) form the backbone for biodiversity conservation worldwide. The effectiveness of protected areas has been studied and it has been shown that confounding factors, such as remoteness and accessibility, correlated with both presence of protection and extractive behaviors, affect the outcomes. We investigated the effectiveness of Madagascar's PA network in decreasing deforestation pressures, using a novel counterfactual methodology, accounting for distance to roads, rivers, major cities and altitude, slope and annual rainfall. The assessment was independently conducted for two different time periods, 1990–2000 and 2000–2010, and for Madagascar's three major forest types. We found that PAs were effective to some extent in reducing deforestation and that some of this decrease can be attributed to the presence of PAs, not just to the confounding factors rendering the land assigned for protection less likely to be deforested. We found differences in PA effectiveness between the two time periods, and in general lower deforestation in the later time period has meant that the PAs have less pressures to resist. However, in the spiny forest, even if deforestation had overall diminished, the pressure on reference areas used to compare PAs seemed to have increased showing that PAs have indeed a mitigation effect and thus increased in effectiveness in the second time period. Our study highlights the alarming trend of what happens once enough forest has been lost in easily accessible areas and the pressures starts to spread to also more remote areas and lands comparable to PAs (remote and inaccessible).

1. Introduction

Designing and managing protected areas (PA) are the main international efforts taken to conserve biodiversity. An increase in the coverage of PAs has long been the aim of international conventions and initiatives (Juffe-Bignoli et al., 2014). With progress towards Aichi Target 11 of protecting ≥17% of the planet's terrestrial areas, the focus has now shifted towards assessing their effectiveness (World Parks Congress, 2014). PA *effectiveness* is however a multifaceted concept (Eklund, 2016) that encompasses aspects as diverse as management evaluations or assessments of species coverage or population viability, or reductions in threats such as deforestation, which has traditionally been evaluated by comparing habitat loss within and outside PAs (Coad et al., 2013; Naughton-Treves et al., 2005; Rodrigues et al., 2004). More recently, and in particular for assessments of reduced deforestation, evaluations have been carried out through a counterfactual approach, where the amount of land conversion within PAs is compared to the amount of conversion in non-protected areas of similar environmental characteristics (Andam et al., 2008; Carranza et al., 2014; Joppa and Pfaff, 2010; Nolte et al., 2013). The need for counterfactual approaches follows from the observation that PAs are generally located away from urbanized centers and at high altitudes (Joppa and Pfaff, 2009), where pressures for land conversion are smaller. As such, when assessing effectiveness, one should compare areas under similar pressure. Studies following such approaches have shown that PAs are effective in mitigating deforestation for many ecosystems across the tropics (e.g. in the rainforests in the Amazon (Nolte et al., 2013), Costa Rica (Andam et al., 2008) and Sumatra (Gaveau et al., 2009) and in the Brazilian Cerrado (Carranza et al., 2014)). Interestingly, few studies were carried out in Africa (but see Green et al., 2013; Rasolofoson et al., 2015). The majority of countries where the impact of PAs have been assessed are middle income nations with institutions better prepared for nature conservation (Bhattarai, 2001).

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http://dx.doi.org/10.1016/j.biocon.2016.09.033

Madagascar provides an interesting setting for the exploration of questions of PA effectiveness. The country has among the highest level of endemism in the world (Goodman and Benstead, 2005), and has repeatedly been identified as a high priority for conservation (Brooks et al., 2006; Funk and Fa, 2010). Previous studies have looked at deforestation and reported high levels of forest loss for the island (Harper et al., 2007; Mayaux et al., 2013). How much of Madagascar was originally forested is debated, but instead of the often repeated 90% - lacking rigorous scientific support - it seems likely that Madagascar has lost up to half (but perhaps less) of its primary forest cover in the last half of the twentieth century (McConnell and Kull, 2014). Reported rates of forest loss vary, most likely as a result of different methodologies, resolutions, and definitions of forest loss (McConnell and Kull, 2014), but all studies report a decrease in deforestation rates from 1990–2000 to 2000–2010 (Harper et al., 2007; Mayaux et al., 2013; Office National pour l'Environnement et al., 2013). However, Madagascar suffers from widespread poverty and its current political situation is unstable (Schwitzer et al., 2014). Madagascar's PA network originated in 1927 and was managed exclusively by the state until the so called Durban Vision promises were made at the 2003 World Parks Congress, where President Ravalomanana announced that Madagascar would triple its PAs in five years (Kull, 2014; Scales, 2014). This led to controversy, and in 2005 approaches deemed more sustainable, such as community management, were promoted to administer the new PAs (Kull, 2014), albeit with little success in mitigating deforestation (Rasolofoson et al., 2015). The effectiveness of the state managed PAs has never been assessed and since they still account for the majority of the protected lands in Madagascar, their effectiveness deserves attention. A coup d'état in 2009 led to an increase in illegal logging (Allnutt et al., 2013; Barrett et al., 2010; Innes, 2010), poaching, and a decline in lemur populations (Platt, 2009). Understanding how effective PAs are at mitigating the threats is crucial to give accurate and policy relevant recommendations.

We develop a new method conceptually based on the counterfactual approach, and applied it separately to different forest types (humid, dry and spiny), as they are recognized as different "ecoregions" with not only unique species composition and structure, but also presumably under different pressures and with different histories (Barrett et al., 2010; Casse et al., 2004; Innes, 2010) We also explored two different time periods, from 1990 to 2000, and 2000 to 2010. This combination of spatial and temporal information is rare for the evaluation of PA effectiveness, and allows to unveil how *effectiveness* varies through time in relation to overall changes in deforestation pressure versus changes in pressure for the more difficult to access areas (that serves as comparisons for the PAs).

2. Methods

2.1. Data

Forest cover for the years 1990, 2000 and 2010 was obtained from layers developed by Office National pour l'Environnement (ONE) and other institutions (Office National pour l'Environnement et al., 2013). Layers are based on the classification of Landsat TM and ETM+ data with a 30 m spatial resolution, see Harper et al. (2007) for classification details. Using 1990 and 2000 forest cover as baselines, we determined if a pixel had been deforested between 1990–2000 and 2000–2010, respectively. Pixels covered by clouds in either the beginning- or end-year were omitted.

Elevation and slope were used at a 90 m resolution while distances to large cities (i.e. cities with a population superior to 100,000 inhabitants by 1993), roads, and rivers and annual precipitation were used at a 500 m resolution (Table 1). We used annual precipitation, in combination with slope and altitude, as a proxy for agricultural suitability (Ramaharitra, 2012), as other available datasets (such as the FAO Global Agro-Ecological Zones) on agricultural suitability were of too low resolution (9 × 9 km) for our analyses.

The PA location, shape and area were gathered from the World Database on Protected Areas (UNEP-WCMC and IUCN, 2015). In our study, we focused exclusively on PAs established in 1990 or earlier for the first time period and those established in 2000 or earlier for the second time period (Fig. 1). Our analyses were based on PAs of categories II (national parks) and IV (special reserves) while we omitted community managed PAs, which were more recently established. For the first time period 39 PAs were included; for the second time period 7 more PAs had been established and were included. We also re-ran the analyses for the second time period, omitting the additional seven newly established PAs to be able to infer the influence they had on the results.

We used the vegetation layers produced by the Critical Ecosystem Partnership Fund (CEPF) Madagascar Vegetation Mapping Project (Moat and Smith, 2007) to classify Madagascar in its three main forest types: humid, dry and spiny. Mangroves were reclassified in either of the three forest types by proximity. The CEPF classification is based on satellite images from 1999 and 2003 from which we could not directly classify forest pixels deforested before 2001. The classification into forest type for these pixels was done by first making polygons for the three main forest types as of the CEPF, and then classifying the remaining pixels according to overlapping polygons (Fig. S1).

2.2. Sampling design

For each of the three forest types considered we extracted a 10% random sample of forested pixels from the first year of each of the two time periods analysed (i.e. 1990 for the first period and 2000 for the second), see Table S1 in supplementary materials. These pixels were then intersected with the aforementioned deforestation covariates (detailed in Table 1).

We omitted pixels that had missing information, generally because of cloud cover, for any of the considered variables. For this reason, in the second time period, a large area of the humid forest was not usable (Table S1).

2.3. Description of quantitative methods

Because of the high resolution of the data, a large number of pixels are extracted even if "only" 10% of the data are considered. Commonly used counterfactual approaches such as matching methods (Andam et al., 2008; Nolte et al., 2013) seemed computationally feasible only if applied to smaller datasets or smaller subsamples likely not representative of the full data. Here we instead propose a new counterfactual approach with the aim to allow us to compare large datasets and that does not limit the comparison to pairs of pixels (protected vs. non-protected).

We use the Mahalanobis distance (Legendre and Legendre, 2012, Section 7.4.1.) on the landscape characteristics to compare each focal pixel (all sample pixels inside PAs) to a group of pixels with similar characteristics. The Mahalanobis distance (D) between a focal pixel $\boldsymbol{p_f}$ and a pixel $\boldsymbol{p}$ with similar characteristics is calculated as follow

$$D = \sqrt{\left(\boldsymbol{p_f} - \boldsymbol{p}\right)^t \mathbf{V}^{-1} \left(\boldsymbol{p_f} - \boldsymbol{p}\right)} \quad (1)$$

where $\boldsymbol{p_f}$ and $\boldsymbol{p}$ are column vectors including information on all the variables characterizing either pixels, $\mathbf{V}$ is the covariance matrix calculated over all pixels in the area considered, t is the transpose of the vector and -1 is the inverse of a matrix. A computationally efficient way to calculate the Mahalanobis distance on a set of pixels is to first calculate the Mahalanobis transformation on a set of pixels that include both the focal pixel $\boldsymbol{p_f}$ and all the other pixel $\boldsymbol{p}$. This can be achieved by performing a principal component analysis with a correlation scaling (Legendre and Legendre, 2012, Section 9.1.4.) on the set of pixel of interest. The Euclidean distance among the Mahalanobis transformed pixels